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A review of offshore wind turbine nacelle: Technical challenges, and research and developmental trends

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ABSTRACT

The turbine nacelle with traditional wind power generation system is heavy, especially in offshore applications due to the large mass of the power frequency step-up-transformer operated at 50 or 60 Hz, and copper conductor generator. For example, the weight and volume of a 0.69/33 kV 2.6 MVA transformer are typically in the range of 6–8 t and 5–9 m^3, respectively. The weight for a 10 MW direct drive permanent magnet generator is about 300 t. These penalties significantly increase the tower construction, and turbine installation and maintenance costs. The tower cost represents 26% of the total component cost of the turbine and on average about 20% of the capital costs are associated with installation. Typical maintenance cost of an offshore wind turbine is about 2.3 cents/kWh, which is 20% higher than that of an onshore based turbine. As alternative approaches to achieve a compact and lightweight offshore wind turbine nacelle, different concepts have been proposed in recent years, such as step-up-transformer-less system, medium-frequency (in the range of a few kHz to MHz) power transformer-based system, multilevel and modular matrix converter-based system and superconducting generator-based system. This paper aims to review the technical challenges, current research and developmental trends, and possible future directions of the research to reduce the weight and volume of the nacelle. In addition, a comprehensive review of traditional wind power generation technologies is conducted in this article as well.

Contents

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1. Introduction

The energy and environment represent two major areas of global crises, but it is becoming more and more obvious that wind energy may offer solutions to these enormous challenges [1]. Wind energy has continued the worldwide success story as the wind power development is experiencing dramatic growth [2–6]. The cumulative growth of wind turbine installation has directly pushed the wind technology into a more competitive area [7–12]. In this propitious climate, it is therefore essential for scientists and researchers to find the most effective technologies for wind power generation systems.

Wind speed varies continuously as a function of time and height because of changes in the thermal conditions of air masses. The motion of air masses is not only a global phenomenon but also a regional and local phenomenon. The annual peak hours are normally around 2500–3000 in good sites. Wind turbine generator converts wind energy to electricity energy. It follows the energy reservation principle. If A is the cross-sectional area through which the air of velocity V flows, and ρ the air density, the theoretical power P available in a wind stream can be calculated from [13,14]

$$P = \frac{1}{2}\rho A V^3. \quad (1)$$

Usually offshore winds tend to flow at higher speeds than onshore winds. This allows the turbine to produce more electricity as the possible energy produced from the wind is proportional to the cube of the wind speed. Also unlike onshore wind, offshore breezes can be strong in the afternoon, matching the time when load demands are at peak level. Moreover, wind farms cover large areas of land. The land area covered by a 3.6 MW turbine can be almost 0.37 km^2; such that 54 turbines would cover about 20 km^2 of land area. Table 1 summarizes the land covered by some offshore wind farms [15–19]. Offshore wind farms save land rental expense which is equivalent to 10–18% of the total operating and maintenance costs of a wind farm. Therefore, offshore based wind farms have attracted significant attention in recent years. According to statistical data, the cumulative installed capacity of offshore wind farms in 2008, 2010 and 2012 was 1.50, 3.08 and 5.41 GW, respectively [20]. The capacity therefore doubled in every two years. Table 2 summarizes the global annually installed capacity of offshore wind farms. It is expected that the global offshore installed capacity will increase to approximately 20 GW by 2015 and rise sharply to 104 GW by 2025. According to the Global Wind Energy Council and Green Peace International estimations it is possible to mitigate 20% of global electricity demand with wind power [21].

Wind turbines are broadly classified into two categories: horizontal axis wind turbines and vertical axis wind turbines. The rotation of main rotor shaft of a horizontal axis wind turbine is in the direction of the wind. The rotor, generator, step-up transformer, and other equipments of a horizontal axis wind turbine are usually integrated in a nacelle placed at the top of the tower. On the other hand, the rotation of rotor shaft of a vertical axis wind turbine is perpendicular to the ground, and in a vertical axis wind turbine, the generator, transformer, converters and other equipments are usually assembled near the ground. Due to its better aerodynamic performances compared with the vertical axis wind turbines, the horizontal axis wind turbines are most commonly used in large-scale offshore wind farms. This paper mainly focuses on the horizontal axis wind turbines.

The turbine nacelle usually houses the generator, power converter, grid side step-up transformer and monitoring and control equipment. The tower provides support to the rotating parts and

Table 1
Offshore wind farms data.

Wind farms	Power capacity (MW)	Distance to shore (km)	Number of turbines	Land covered (km^2)
Barrow	108	7	30	10.00
Gunfleet Sands	172	7	48	17.50
Horns Rev	160	15	80	20.00
Horns Rev 2	200	27	91	35.00
Lynn and Inner	194	9	54	20.00
Ormonde	150	10	30	8.70
Princess Amalia	120	23	60	14.00

Table 2
Global offshore wind farms installed capacity.

Year	Annual addition (MW)	Cumulative (MW)
2002	170	256
2004	110	633
2006	93	816
2008	373	1507
2010	999	3083
2012	1293	5410

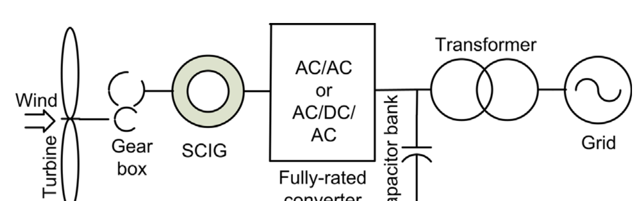


Fig. 1. Constant speed wind power generation system with SCIG.

nacelle (the stationary parts). The nacelle weight of a 5 MW turbine is about 300 t, while the rotor represents only about 120 t. Therefore, the tower diameter and strength depend mostly on the weight of the nacelle and expected wind loads. The tower cost accounts for 26%, the largest component, of the total turbine component cost [22].

The tower is normally held by a heavy foundation to ensure it withstands the overturning moment created from the turbine. The foundation size of a 2.3 MW wind turbine is 314 m^2 and the approximate weight is 2000 t or more [23]. In an offshore area, the cost of installation is extremely high. On average, approximately 20% of the capital costs are associated with installation [24,25]. Therefore, a reduction in mechanical loading represents an enormous saving in terms of tower construction and turbine installation costs.

As the power rating and the distance of the wind farm from the shore increase, the engineering challenges associated with the installation and maintenance of the power generation systems also grows. Recently, many researchers/scientists have begun to focus on a number of areas including: proposing medium-voltage converter to eliminate the step-up-transformer, applying medium-frequency transformers to reduce the weight and volume of step-up-transformers, and superconducting wind generators to reduce the weight and volume of wind turbine generators. These steps are aimed at reducing the weight and volume of the wind power generation systems. The weight and volume reduction of wind turbine power generation system (WTPGS) still needs further investigation because wind power has become one of the main sources of renewable energy for future electricity supply within smart microgrids.

This article presents a technology review of traditional WTPGS, which is mainly focused on the horizontal axis wind turbine nacelle. A survey of most recent research and development in weight reduction of wind turbine nacelle is conducted. The challenges, research trends and possible future directions of the research in lightweight WTPGS for offshore applications are addressed in this paper.

2. Offshore wind power generation systems

Wind turbines can operate with either fixed speed or variable speed. The actual rotational speed of a wind turbine is quite low and not fixed in nature. Therefore, the turbine speed must be adjusted to suit the electrical frequency. This can be done in two ways: either with a gearbox or with the number of pole pairs of the generator. The pole pair sets the mechanical speed of the generator with respect to the electrical frequency and the gearbox adjusts the rotor speed of the turbine to the mechanical speed of the generator. The gearbox-based system has shorter lifetime and requires frequent maintenance. The efficiency and armature diameter of an induction machine depend on the number of poles. The increase in the number of poles may decrease the efficiency and increase the magnetizing currents. There are two main types of wind power generation systems: (1) the constant speed wind power generation system and (2) the variable speed wind power generation system.

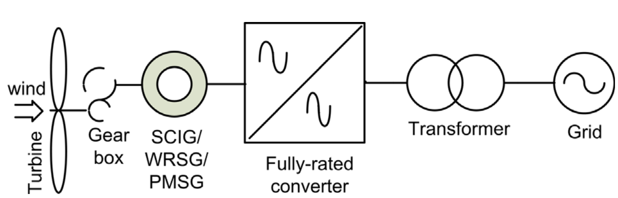


Fig. 2. Variable speed wind power generation system with fully-rated power converter.

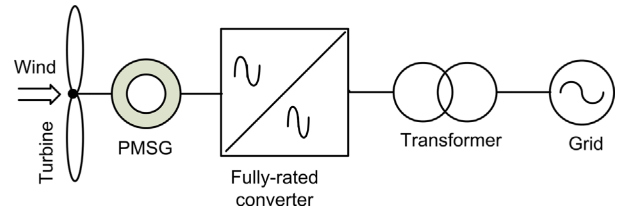


Fig. 3. Variable speed direct drive (gearbox less) wind power generation system with synchronous generator and fully-rated power converter.

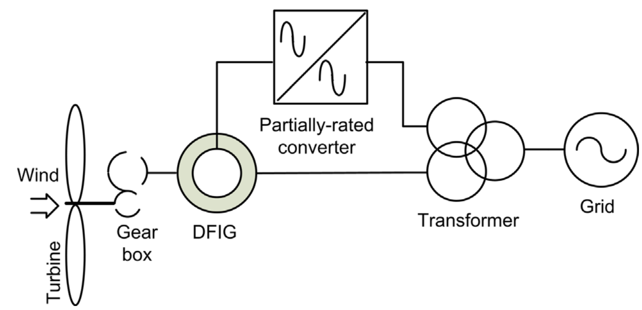


Fig. 4. Variable speed wind power generation system with partially-rated power converter.

2.1. Constant speed wind power generation system

In this system, the wind turbine is a fixed speed controlled machine, with a squirrel cage induction generator (SCIG) directly connected to the grid through a power converter and a step-up-transformer, as shown in Fig. 1. Since the SCIG always draws reactive power from the grid, this system uses a capacitor bank for reactive power compensation. It is called the Danish concept and it was very popular in the 1980s.

Because of its robustness, mechanical simplicity and low price, many developing countries have installed this constant speed wind power generation system. However, this system suffers from rotor speed instability. An analysis of rotor speed stability was carried out in [26] to determine whether rotor speed stability could be achieved through the help of reactive power compensation. It was found that the rotor speed stability of a constant speed wind power system could be improved by active stall [27].

2.2. Variable speed wind power generation systems

According to the power rating of the converters, the variable speed wind power generation systems can be classified into two groups: (1) the fully-rated converter-based system, and (2) the partially-rated converter-based system.

2.2.1. Fully-rated converter-based system

This system consists of a variable speed wind turbine, and the generator connected to the grid through a full scale converter and a step-up-transformer. The converter performs the reactive power compensation and the smoother grid connection. The generator can be excited electrically (wound rotor synchronous generator, WRSG or SCIG) or by a permanent magnet (permanent magnet synchronous generator, PMSG). Due to the variable speed operation, it is possible to continuously adapt the rotational speed of the wind turbine according to the wind speed. As a result, the generator speed changes with the variation in wind speed. Due to its low maintenance cost and wide range control capability, the

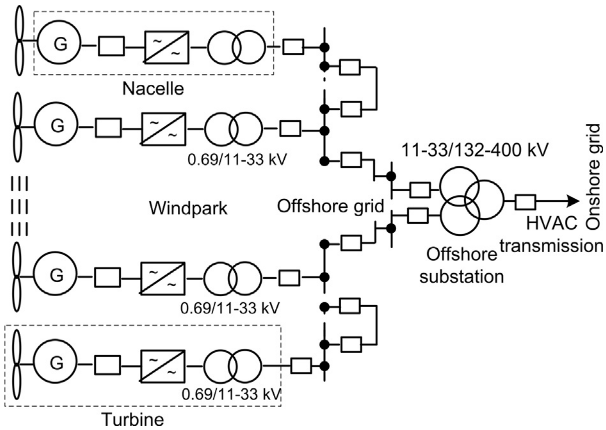


Fig. 5. Most common layout of the HVAC transmission line-based offshore wind farms.

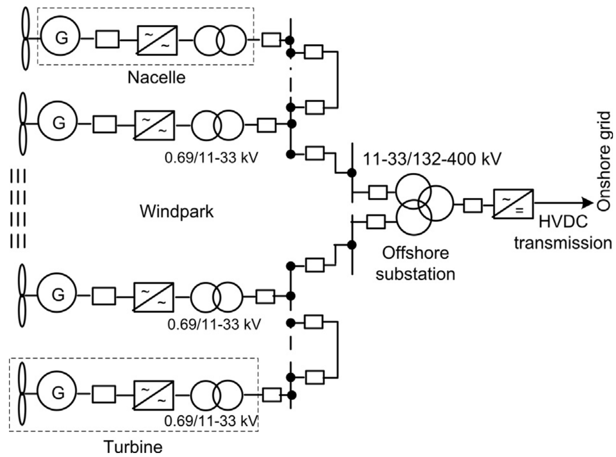


Fig. 6. Most common layout of the HVDC transmission line-based offshore wind farms.

fully-rated power electronics based synchronous generator wind power system has proved to be an attractive solution for offshore applications. There are two types of variable speed wind power generation systems with full rating power converters. The first is the variable speed wind power generation system with the synchronous/induction generator and gearbox, as shown in Fig. 2. The second is the variable speed direct drive (gear less) wind turbine with synchronous generator, as illustrated in Fig. 3, where the synchronous generator can be designed with multiple poles, which implies that there is no need for a gearbox.

A development and performance analysis of such a system has been carried out in [28]. In [29], a novel active and reactive power control technique was proposed for a variable speed wind turbine with a fully-rated power electronic conversion system which can maintain the maximum converter efficiency and extract the maximum power. In addition, PMSGs have high torque density and an absence of excitation losses.

2.2.2. Partially-rated converter-based system

This system consists of a variable speed wind turbine with a doubly fed induction generator (DFIG), and a partially-rated power converter (approximately 30% of generator power) on the rotor circuit, as depicted in Fig. 4. The stator is directly connected to the grid, while a partially rated power converter controls the rotor frequency and the rotor speed. The partially rated converter performs the reactive power compensation and the smoother grid connection. Because the power electronic converter has a power rating of approximately 30% of the system rated power, this system can not only increase energy transfer efficiency and decrease mechanical stress, but also achieve the decoupling control of the generator's active and reactive powers.

The modeling and simulation of the variable speed wind turbine system with a DFIG has been analyzed in [30,31]. The authors in [32–34] proposed different control techniques. The main drawbacks of the DFIG-based system are the use of slip rings and a protection issue in the case of grid faults. The brushless operation of the brushless doubly fed machine (BDFM) has already attracted interest owing to the use of the wind power conversion system. The BDFM maintains all the features of the DFIG but also achieves brushless operation. An analysis, design and control of BDFM have been done in [35]. A slot harmonic BDFM has been designed and analyzed to improve the performance of the BDFM in [36]. The development and performance of a variable speed wind turbine system with a BDFM was analyzed in [37,38] and different control techniques were implemented in [39–41].

3. Offshore wind power transmission systems

The existing offshore wind farm consists of on average 50 wind turbines installed in an offshore area (more than 7 km from the shore) [15–19]. A medium voltage (11–33 kV AC) local grid is used to collect the generated power from individual turbines. This collected offshore power is fed to the onshore main grid using a high voltage AC (HVAC) or high voltage DC (HVDC) transmission line.

3.1. HVAC technology

Most of the existing offshore wind farms use HVAC technology. The most common layout of the HVAC transmission line-based offshore wind farm is shown in Fig. 5. The variable frequency and variable magnitude power from the generator is converted into fixed frequency and fixed magnitude power using a two-level power converter. To integrate the scattered wind turbine generators into a medium-voltage grid (e.g. 11–33 kV) before the voltage step-up for long distance transmission, a power frequency (50 or 60 Hz) step-up transformer is commonly used to step-up the voltage. This offshore wind power is fed to the onshore main grid (132–400 kV) using three-phase underground and submarine HVAC cables through an offshore substation. The Horns Rev offshore wind farm in Denmark (160 MW) uses an 170 kV AC marine transmission line to transport wind power to an onshore main grid [42]. The charging current of cable capacitance may become too high as the cable length increases and this can greatly reduce the effective power transfer capability. Considering the wind speed and capacitance effect of the HVAC cables, offshore wind turbines are usually installed about 7–30 km from the shore. HVAC systems are established technology and they have a lower cost than the HVDCs when the transmission distance is shorter than 50 km.

3.2. HVDC technology

The HVDC technology eliminates the cable capacitance effect, thus it is more economically feasible than HVAC technology for power transmission to a distance of above 50 km. The HVDC system provides a considerable cable, installation and maintenance cost reduction, and the fault rate is reduced as well. The development of the classical HVDC technology started in the 1940s. This technology is thyristor-based and well-proven. A thyristor-based power converter is used to convert the HVAC to HVDC.

In the late 1990s, voltage source converter based HVDC (VSC-HVDC) technology was introduced commercially, where IGBTs are used as switching devices. Compared with the classical HVDC solution, the VSC-HVDC solution features compact architecture and provides more controllability, which is important for offshore applications. ASEA Brown Boveri (ABB) and Siemens have been delivering VSC-HVDC systems with trade mark of HVDC light and HVDC plus, respectively. The Cross Sound cable is an 150 kV HVDC light underwater cable link between New Haven and Shoreham in USA, with a power of 330 MW and a cable distance of 40 km [42]. The Basslink interconnector in Australia is the first HVDC interconnector to use the latest Siemens control systems and connects the 500 kV transmission system in Victoria to the 220 kV transmission system in Tasmania. Basslink is a 290 km undersea cable-based 400 kV DC electricity interconnector, which is rated to transmit 500 MW of energy [42]. The most common layout of the HVDC transmission line-based offshore wind farm is shown in Fig. 6.

4. Wind turbine generators

The generator provides a means of energy conversion between the mechanical torque from the wind rotor turbine, as prime mover, and an electrical load or grid. Large size wind turbines are able to generate more electricity at lower cost compared to the smaller turbines. This is because the setup costs and maintenance costs do not depend on the size of the machine. Due to this, the output power of today's wind generators has exceeded 7 MW. For example, since 2011, Enercon has been producing a wind turbine E-126/7500 with a power capacity of 7.5 MW [43]. Currently, Sway Turbine and Windtec Solutions are developing 10 MW wind turbine generators, which are expected to be commercially available by 2015 [44,45].

Although the power rating of wind generators has been increasing gradually, the voltage rating of the most common generators is usually in the range of 380–690 V. The exception is Repower which employs 6.6 kV DFIG. Table 3 summarizes the voltage ratings of a few common wind turbine generators [45–49]. As can be seen, the converter voltage level is also in the range of 380–690 V due to the lower generator voltage rating and the use of two-level converter topology. With exception of the DFIG systems, all the other types of generator systems require full-scale converters.

Basically, a wind turbine can be equipped with induction or synchronous machines. Several types of machines (asynchronous and synchronous) are commonly used in offshore WTPGS. Currently, asynchronous machines dominate wind turbine applications and hold a 70% share of wind turbine generators.

4.1. Squirrel cage induction generator (SCIG)

Sinovel and Siemens employ SCIG, which is the most common generator used in wind turbines. Because of its mechanical simplicity, high efficiency, low maintenance requirements, small percentage speed changes and low price, the SCIG is used for constant speed wind turbine systems. The induction generator is provided with two windings, one on the stator, and the other on the rotor. The stator winding of the induction machine has two functions. It provides the excitation or magnetization, and carries the armature or generated current. The rotor winding only carries the armature current. When AC excitation is present, the magnetic field rotates at a speed determined jointly by the number of poles in the winding and the frequency of the current, i.e. the synchronous speed. If the rotor rotates at a speed other than the synchronous speed, an emf is generated in the rotor winding at a frequency corresponding to the difference between the two speeds, known as the slip frequency. SCIGs have a steep torque speed characteristic and this means that fluctuations in wind power are transmitted directly to the grid. The rotor is a cylinder mounted on a shaft. Internally it contains longitudinal conductive bars (usually made of aluminum or copper) set into grooves and connected together at both ends by shorting rings which form a cage-like shape. The name is derived from the similarity between the rings-and-bars winding and a squirrel cage [50,51]. The machine as a generator is not self excited (it requires magnetizing kVAR) and this presents a major problem. The magnetizing current is drawn from the power distribution network to which the generator is connected. Capacitor banks connected in parallel to the generator can, if they are in the right size, compensate for the magnetizing or reactive power drawn by the generator. The stator windings of the generator take the magnetizing current from the grid, so the full load power factor is relatively low. Also, there is a voltage instability problem at the moment of grid fault and when the fault is cleared. SCIGs can be used both in fixed-speed wind turbines and in full variable speed wind turbines. In variable speed system, the variable frequency power of the machine is converted to fixed-frequency power by using a bidirectional power converter.

Table 3
Wind turbine generator voltage rating.

Turbine power (MW)	Voltage (V)	Model	Manufacturer
1.50	575	1.5_{SLE}	GE Energy
1.65	690	Wt1650	Windtec
2.05	575	MM92	Repower
3.00	400	E-82 E3	ENERCON
5.00	690	Bard 5.0	Bard Engineering
5.50	690	Wt5500	Windtec
10.00	690	SeaTitan	Windtec

4.2. Wound rotor synchronous generator (WRSG)

Enercon uses WRSG for wind turbine systems. The synchronous machine is usually built with a rotor which carries the field system and provides a winding excited by the DC. The stator carries a three-phase winding quite similar to that of the induction machine. The rotor may have salient poles, or may be cylindrical. Salient poles are more usual in slow speed machines, and may be the most useful version for application to wind turbine generators. The stator windings of WRSGs are connected directly to the grid and hence the rotational speed is strictly fixed by the frequency of the supply grid. The rotor winding is excited with a direct current using slip rings and brushes or with a brushless exciter with a rotating rectifier. Unlike the induction generator, the synchronous generator does not need any further reactive power compensation system. The rotor winding, through which the direct current flows, generates the excitation field, which rotates at the synchronous speed [50,51]. The speed of the synchronous generator is determined by the frequency of the rotating field and by the number of pole pairs of the rotor. But the price that has to be paid for such a gearless design is a large and heavy generator and a full-scale power converter that has to handle the full power of the system. It may be used, at a constant speed, and fixed to the net frequency with consideration of the drive train dependencies and synchronization at start-up. The WRSG may also be applied using a full power inverter, with the option of variable speed operation. In all cases, it is necessary to excite the rotor winding with the DC, using slip rings and brushes, or a brush-less exciter employing a rotating rectifier.

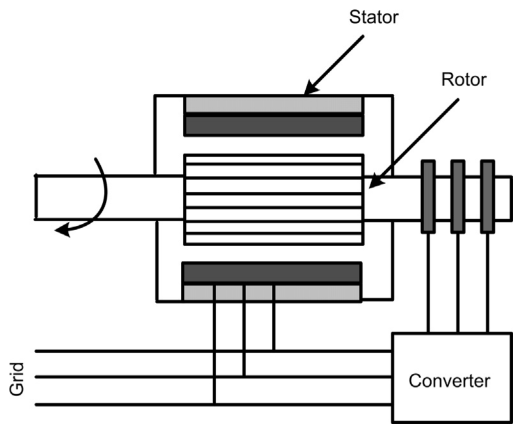


Fig. 7. Principle of DFIG.

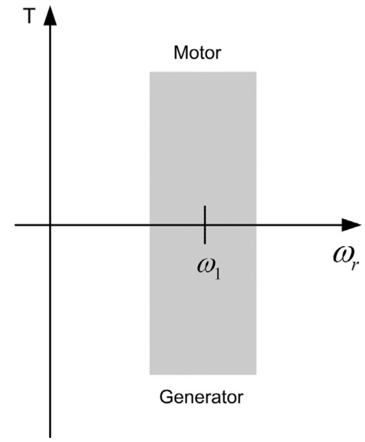


Fig. 8. Speed-torque characteristics of DFIG.

4.3. Permanent magnet synchronous generator (PMSG)

GE energy, Vestas, Gamesa, Siemens and Goldwind employ PMSGs. The stator of PMSGs is wound, and the rotor is provided with a permanent magnet pole system and may have salient poles or may be cylindrical. Typical low-speed synchronous machines are of the salient-pole type and feature many poles. If a synchronous generator has an appropriate number of poles (a multi-pole PMSG) it can be used as direct-drive system. The most common types are the radial flux machine, the axial flux machine and the transversal flux machine. In the PMSG machine, the efficiency is higher than that in the induction machine, as the excitation is provided without any energy supply. However, the materials used for producing permanent magnets are expensive, and they are difficult to manufacture. Additionally, the use of PM excitation requires the use of a full scale power converter in order to adjust the voltage and frequency of generation to the voltage and the frequency of transmission, respectively, which in turn, increases the system cost. However, the benefit is that the power can be generated at any speed so as to fit the current wind conditions. Maintenance is generally restricted to bearing lubrication only [50,51]. A major problem is the necessity of maintaining the rotor temperature below the maximum operating temperature of the magnet, which may be limited by the Curie point of the magnetic material, and also by the thermal properties of the binding material in the case of powder metallurgy composites. Also, the synchronous nature of the operation causes problems in relation to start-up, synchronisation, and voltage regulation.

4.4. Doubly-fed induction generator (DFIG)

Repower has been developing wind turbine using DFIG. Only slip power losses set the limit for the rotor speed of an induction machine if it is allowed to vary the rotor speed. When the slip power losses are high, the efficiency of the machine becomes low. To regulate the rotor speed beyond this limit and reduce the slip power loss it is essential to doubly excite the stator and rotor windings. All electric machines can be categorized as either singly-fed, with one winding set that actively participates in the energy conversion process or doubly-fed, with two active winding sets. DFIG is based on an induction generator with a multiphase wound rotor and a multiphase slip ring assembly with brushes for access to the rotor windings. The principle of the DFIG is that rotor windings are connected to the grid via slip rings and a converter that controls both the rotor and the grid currents. Thus rotor frequency can freely differ from the grid frequency. By using the converter to control the rotor currents, it is possible to adjust the active and reactive power fed to the grid from the stator independently of the generator's turning speed. The control principle used is either the two-axis current vector control or direct torque control (DTC). The doubly-fed generator rotors are typically wound by 2–3 times the number of turns of the stator. This means that the rotor voltages will be higher and the currents correspondingly lower [52]. Thus in the typical $\pm 30\%$ operational speed range around the synchronous speed, the rated current of the converter is lower which leads to the lower cost of the converter. When the rotor moves faster than the rotating magnetic field from the stator, the stator magnetic field induces a strong current in the rotor. The faster the rotor rotates, the more the power will be transferred as an electromagnetic force to the stator, and converted in turn to electricity which is then fed into the electrical grid. The speed of the generator will vary with the turning force applied to its rotor. The percentage difference between this speed and the synchronous speed is called the generator's slip, which sets the frequency of the generated voltage [52]. The schematic diagram of DFIG is illustrated in Fig. 7 [53]. DFIG can be operated both in motor and generator operations with a rotor speed, ω_r around the synchronous speed ω_1. The speed–torque characteristics of the DFIG are shown in Fig. 8 [53].

Because the losses in the converter circuit depend on the current through the valves, it is important to have an appropriate ratio of stator to rotor turns of the DFIG that can minimize the rotor current without exceeding the maximum available rotor voltage. By way of summary, a doubly-fed induction machine is a wound-rotor doubly-fed electric machine and it has several advantages over a conventional induction machine in wind power applications. Firstly, as the rotor circuit is controlled by a power electronic converter, the induction generator is able to both import and export reactive power. This has important consequences for power system stability and allows the machine to support the grid during severe voltage disturbances (e.g. low voltage ride through, LVRT). Secondly, the control of the rotor voltages and currents enables the induction machine to remain synchronized with the grid while the wind turbine speed varies.

To overcome the drawbacks of DFIG, more attention needs to be focused on other types of DFIG, such as a cascaded doubly fed induction machine, and single frame doubly fed induction machine.

4.4.1. Cascaded doubly-fed induction machine

Compared to a variable speed singly-fed machine arrangement with a cage induction machine, the single doubly-fed induction machine (SDFM) has the advantage of a reduced power converter rating, which is related to the desired speed range. Nevertheless, it

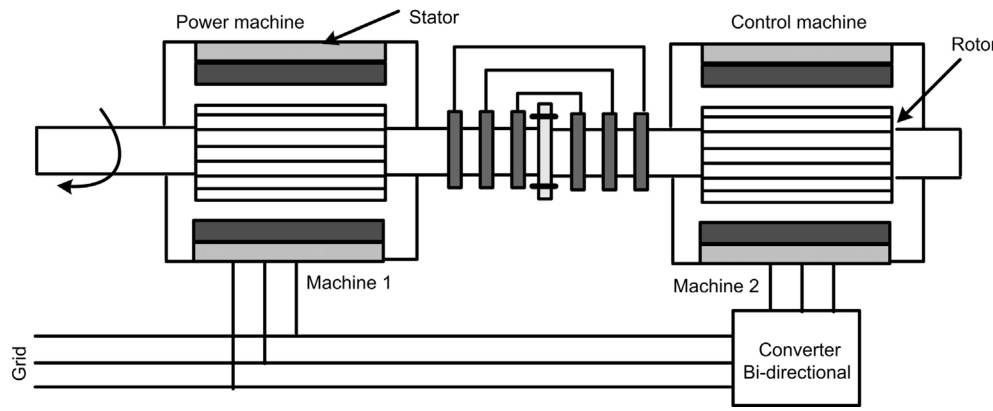


Fig. 9. Cascaded doubly-fed induction machine arrangement.

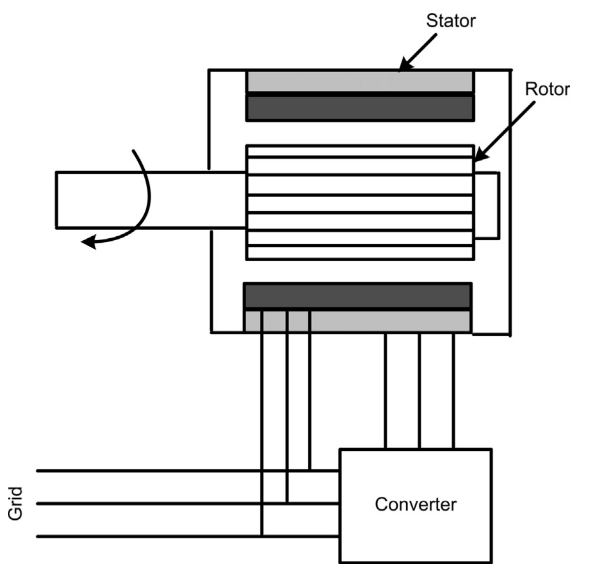


Fig. 10. Layout of the BDFM.

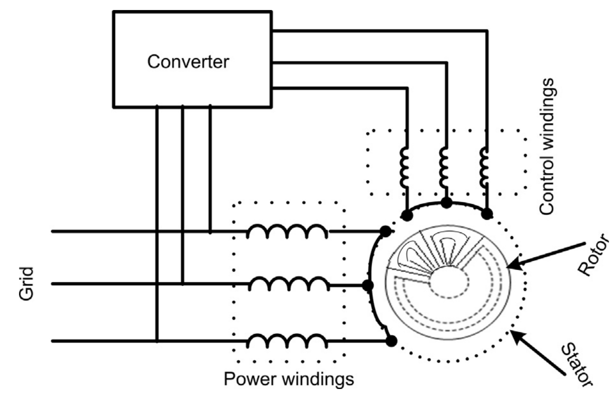


Fig. 11. Equivalent circuit layout of the BDFM.

still has a drawback: the SDFM has slip-rings and brushes on the rotor side, which are subject to maintenance and additional costs. The cascaded doubly-fed induction machine consists of two doubly-fed induction machines that are connected mechanically through the rotor and electrically through the stator circuits as shown in Fig. 9. The stator circuit of one of the machines is directly connected to the grid while the other machine's stator is connected via a converter to the grid. Since the rotor voltages of both machines are equal, it is possible to control the induction machine that is directly connected to the grid with the other induction machine. It is possible to achieve decoupled control of active and reactive power of the cascaded doubly-fed induction machine in a manner similar to the doubly-fed induction machine [54]. Since the two rotors have a stiff mechanical coupling, no brushes are needed for the slip-ring connection which can eliminate the drawback of SDFM. But due to a large amount of windings, the losses are expected to be higher than that for a standard doubly-fed induction machine of a comparable rating. In the past century, this type of concept has been continuously improved. In 1907, Hunt [55] conducted a remarkable evaluation of the cascade connection concept in a single machine. Further developments were made to the stator and rotor designs by Creedy in 1921 [56]. In 1966, Smith [57] proposed the concept of non-linking of stator fields of cascade induction machines by spatial separation. A significant contribution to the design of the self-cascaded machine was demonstrated by Broadway and Burbridge in 1970 [58]. The control principle of the cascaded machine was proposed in 1983 by Shibata et al. [59].

4.4.2. Single frame doubly-fed induction machine

The brushless doubly-fed machine is an induction machine with two sets of symmetrical AC windings in the stator. One winding is for the power and the other for the control. To avoid a direct transformer coupling between the two stator windings, they cannot have the same number of pole pairs. Furthermore, to avoid unbalanced magnetic pull on the rotor, the difference between the pole pairs must be greater than one. The number of poles in the rotor must equal the sum of the number of poles in the two stator windings. In the arrangement, as shown in Figs. 10 and 11 [38,53], one winding, the power winding, which is connected directly to the mains or grid, has a pole-pair number of P_p and a frequency of f_p. The other winding, the control winding, which is supplied with variable voltage at variable frequency from a converter connected to the mains or grid, has a pole-pair number of P_c and a frequency of f_c. At running, there are two rotating magnetic fields in the machine which induce electrical potential to generate current. The rotational speed, n_r of BDFM can be calculated from [60]

$$n_r = \frac{60(f_p \pm f_c)}{P_p + P_c}. \tag{2}$$

The "+" operation symbol is used if the electrical source phase sequence of power winding is the same as that of control winding or the "−" symbol is used. For the above relation it is clear that the machine speed is a function of the frequency of the power winding and the frequency of control winding. In the BDFM-based wind

Table 4
Weight of commonly used offshore wind turbine.

Turbine	Capacity (MW)	Tower (t)	Rotor (t)	Nacelle (t)
Vestas V80	2.00	130	37	67
Siemens 2.3-93	2.30	134	60	82
Siemens 3.6-107	3.60	180	95	125
Repower 5M	5.00	225	120	300

Table 5
Capital costs of offshore wind farms.

Wind farm	Capacity (MW)	Cost (million)		Cost/MW*	Year online
		Cost	Currency		
Kentish F.	90	105	GBP	2.14	2005
OWEZ	108	217	Euro	2.54	2006
Lillgrund	110	1800	SEK	2.38	2007
Robin Rigg	180	420	Euro	3.62	2008
Rhyl Flats	90	190	GBP	3.47	2009
Gunfleet S.	172	3900	DKK	3.75	2010

* Approximate cost in million USD/MW; exchange rates are chosen as respective years.

power generation system, the variable speed constant frequency power generation can be achieved by adjusting the frequency f_c of control winding to a different wind speed.

In 1989, the authors in [61] developed the dynamic model of BDFM. An investigation on the effects of various design strategies and a characterization of the BDFM was done in 1990 [62,63]. By using direct mathematical transformation, a two-axis model of cage-rotor BDFM was proposed in [64] and the simulation results were also published in [65]. The design of the BDFM is complicated due to the complexities of determining the overall electric loading and magnetic loading and dividing them between the two stator windings. In order to overcome the direct coupling, the two stator windings should have different pole numbers. Now it is common to use two separate windings in the stator [66–68]. To improve the performance many concepts are developed by optimizing the machine structure (mainly on stator) [69–71]. The rotor of the BDFM is specially designed to couple both stator fields and the machine performance is highly dependent on the structure of rotor windings. The switching efficiency of the magnetic poles of the BDFM is determined by the rotor structure, and hence a special rotor structure is essential to improve the switching efficiency. Multiform rotor structures were studied by the scholars for the optimization of the rotor structure [72–75].

5. Turbine step-up transformers

Power ratings of 2–5 MW per turbine are becoming common for offshore wind farms, where the voltage level of the wind generator is usually in the range of 380–690 V [15–19]. To integrate the scattered wind turbine generators into a medium-voltage grid before the voltage step-up for long distance transmission, a step-up transformer is commonly used to step-up the voltage. In an offshore wind turbine generation system, this transformer is usually installed inside the nacelle together with other equipment, such as the generator and power converter at a height of about 80 m.

Several vendors have been developing special transformers for wind turbine generator systems aimed at reducing the size and weight. ABB has been delivering worldwide vacuum cast coil transformers and liquid-filled transformers for offshore wind farm applications. Cast coil dry type transformers are non-flamable and moisture proof. They feature a solid isolation system which is discharge free. The volume and weight of a 2.5 MVA vacuum cast coil transformer are about 8.5 m^3 and 6200 kg, respectively and no-load and full-load losses are 5.8 kW and 25 kW, respectively [76]. However, dry type transformers can be sensitive to water, micro-cracks, temperature variations, and pollution which can block cooling ducts. A liquid-filled 2 MVA transformer is about 5.7 m^3 in volume and 4530 kg in weight with 870 kg of liquid as the coolant and insulator [77]. The no-load and full-load losses are approximately 3.2 kW and 21 kW respectively. Pauwels developed the SLIM transformer which is compact in size and features that no-load losses are typically half those of the dry-type transformer. A 33/0.69 kV, 2.6 MVA SLIM transformer has a no-load loss of 2.6 kW and a full-load loss of 22.5 kW [25]. The volume and weight of a 20/0.69 kV, 2.3 MVA Bio-SLIM transformer are about 4 m^3 and 5040 kg, respectively [78]. The use of about 900 kg or more silicone fluid as the coolant and insulator in these transformers ensures a high degree of fire safety; the flash point of mineral-oil dielectric is about 150 °C, whereas the silicone fluid's flash point is about 360 °C.

This heavy and large size step-up-transformer significantly increases the weight and volume of the nacelle as well as increasing the mechanical stress of the tower. These penalties are critical in offshore applications, where the cost of installation and regular maintenance is extremely high. For example, an offshore wind farm requires about 20% higher operating and maintenance cost compared with an onshore farm.

6. Turbine component costs

On average, more than 220 t steel is required to build a 5 MW turbine tower and about 130 t steel is required to build a 2 MW turbine tower. Nowadays this has become a critical issue as the turbine size increases. The typical weights of the different major parts of the 2–5 MW offshore wind turbines are summarized in Table 4 [25,79].

At the current pricing levels, a 5 MW offshore wind turbine costs about 18.5 million USD, while an onshore wind turbine of the same power rating would be about 10 million USD [80]. The tower cost accounts for 26%, the largest component, of the total turbine component cost, whereas the generator and power converter represents only 3% and 5% of the total cost, respectively [22]. The turbine blade cost represents 22%, the second largest component, of the total turbine component cost. In a gearbox based system, the gearbox accounts for 13% of the total cost. The bulky and heavy traditional components add significantly to the mechanical loading of the tower although new designs aim to reduce the component size and weight. Reduction of mechanical loading means enormous saving of tower construction cost.

7. Turbine installation cost

The costs associated with developing, engineering, equipment procurement and delivering/constructing an offshore wind farm can be defined as the total capital cost. According to an energy research group report the first two activities contribute about 10% and the third contributes 40–60% of the total capital cost [79]. The total capital cost was about 2.2 million USD/MW in 2005 and almost 3.5 million USD/MW in 2009. The estimated capital cost of a few offshore wind farms is summarized in Table 5. Construction involves fabricating, assembling and installation and contributes 20–40% of the total cost. The installation cost is a fractional

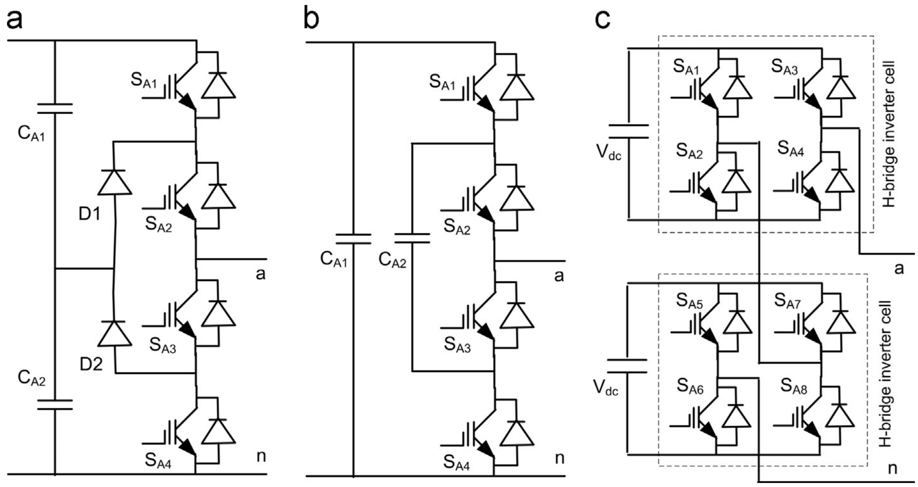


Fig. 12. Single-phase converter circuit diagram: (a) 3-level NPC, (b) 3-level FC, and (c) 5-level MMC.

Table 6
Cost and performance of different converters (3-phase, 11 kV, 250 A).

Converter topology	5-Level			11-Level		
	NPC	FC	MMC	NPC	FC	MMC
IGBTs	48	48	48	60	60	60
Diodes	36	–	–	270	–	–
Capacitors	–	18	–	–	135	–
Total comp.	84	66	48	330	195	60
ALOs*	19	19	23	47	47	55
Total cost (AU$)	90,962	113,131	82,027	115,663	125,359	82,159
THD (%)	17.28	17.80	18.13	7.07	7.28	7.70

* Number of arithmetic and logic operations (ALOs) is used to calculate the complexity of control circuit.

Table 7
Overall comparison of different converters (3-phase, 11 kV, 250 A).

Converter topology	5-Level			11-Level		
	NPC	FC	MMC	NPC	FC	MMC
Performance	0.92	0.97	1.00	0.00	0.02	0.05
Complexity	0.00	0.00	0.12	0.78	0.78	1.00
Cost	0.21	0.72	0.00	0.78	1.00	0.00
Total index	1.13	1.69	1.12	1.56	1.80	1.05

component of capital cost and it is estimated at 10–30% of the total cost as available in the existing literature [23,14]. On average, the turbine installation cost was 0.42 million USD/MW in 2005 and 0.75 million USD/MW in 2010. The weight reduction of the wind turbine can reduce the installation cost as well as the total capital cost of offshore wind farms.

8. Research and development for compact and lightweight wind turbine nacelle

Nowadays in offshore wind farms, it is common to assemble the nacelle with other equipment such as blade and spinner, at a height of about 80 m. The nacelle houses mainly gearbox, mechanical brakes, hydraulic cooling devices, generator, power converter, and transformer. Section 8 covers the research and development trends on generators, power converters and step-up-transformers to reduce the weight and volume of the WTPGS.

8.1. Elimination of turbine step-up-transformer

Elimination of heavy and large grid side step-up-transformer from the nacelle means significant reduction of weight and size of WTPGS. Medium-voltage power electronic converters like multi-level converter topology and modular matrix converter topology have been gaining the popularity to eliminate the grid side step-up-transformers in recent years.

With the arrival of new high-power semiconductor devices, new power converter structures are conceived to meet the needs of future medium or high-voltage converter systems. In this highly active area, neutral point clamped (NPC), flying capacitor (FC) and modular multilevel cascaded (MMC) converter topologies and circuits as shown in Fig. 12 have found their application in low-voltage applications [81,82].

For medium or high-voltage applications, however, the selection of multilevel converter topology is very critical. The number of auxiliary capacitors of FC converter scales quadratically with the number of levels. Also, the voltage balancing becomes a significant problem for high-level numbers [83]. The component numbers of the MMC converter scales linearly with the number of levels and the individual modules are identical and completely modular in construction and hence enable high-level number attainability. High-level converter implies elimination of power transformer and lower total harmonic distortion (THD) with lower switching frequency, eliminating the output filters and reducing running cost [84]. High-level number attainability also allows lower level of DC-link voltage requirement for each H-bridge cell that eliminates boosters. Moreover, in the case of a fault in one of these modules, it is possible to replace it quickly and easily. A comparative study among these three multilevel converter topologies is carried out as summarized in Table 6. Based on performance, complexity and cost, the overall comparison is carried out as summarized in Table 7. The MMC topology has gained the lowest index value, which means this topology is the feasible choice for medium-voltage converter applications. The high number of levels means that medium-voltage attainability is possible with lower-voltage devices to connect the wind turbine to the medium-voltage network directly and also possibility to improve the output power quality. The component number and control complexity increases linearly with the increase of level number. Therefore, the optimal selection of number of inverter levels is important for the best performance/cost ratio of the WTPGS. Different converters (9–21 levels) are analyzed for transformer-less 11 kV grid connections, where the generator output voltage is considered at 690 V. Table 8 illustrates the summary of the converters. Final comparison with

Table 8
MMC converters comparison (3-phase, 11 kV, 250 A).

Level number	9	11	13	15	17	19	21
IGBTs	48	60	72	84	96	108	120
IGBT rating (kV)	4.5	3.3	3.3	2.5	2.5	1.7	1.7
DVUF* (%)	90	90	75	96	84	99	90
THD (%)	9.60	8.20	6.90	6.00	5.20	4.30	4.25
Cost (AU$)	86,400	82,159	98,577	50,400	57,600	36,670	40,744
ALOs	44	55	66	77	88	99	110

* Device voltage utilization factor (DVUF).

Table 9
Overall comparison of MMC converters (3-phase, 11 kV, 250 A).

Number of levels	9	11	13	15	17	19	21
Performance	1.00	0.74	0.49	0.33	0.18	0.01	0.00
Complexity	0.00	0.17	0.34	0.50	0.67	0.83	1.00
Cost	0.80	0.73	1.00	0.22	0.33	0.00	0.06
Total index	1.80	1.64	1.83	1.05	1.18	0.84	1.06

these seven different converters is summarized in Table 9. The 19-level converter has gained the lowest index value, which means this topology is the feasible choice for 11 kV network applications.

However, the MMC converter requires multiple-isolated and balanced DC sources that must be balanced as shown in Fig. 13, and therefore its application is not straightforward, especially in wind power generation systems. Many researchers have addressed their efforts to proposing special modulation techniques [85], switched DC voltage sources and low-frequency phase-shifted transformer feeding [86]. The first two approaches do not give an overall solution and the third introduces a complicated three phase heavy and large transformer.

8.1.1. Multi-coil generator-based medium-voltage converter

Direct drive ensures lower maintenance cost and complexity by eliminating the single or multiple stage gearboxes (three stage gearboxes are commonly used). Besides the major manufacturers, several newer manufacturers such as Mitsubishi, Leitwind, Harakosan and Vensys are introducing offshore wind turbines based on direct drive PMSGs. A new type of lightweight ironless-stator modular direct drive generator, known as the spoked lightweight machine (SliM) was proposed in 2005 for direct-drive wind turbine power generation systems [87]. This is a permanent magnet generator (PMG) with a large number of magnets placed on the steel rotor rim. Copper coils are accommodated on the non-iron inner stator rim. The ironless stator and gearbox free operation allow a lightweight structure but still require a grid side step-up-transformer. In 2006, a study was carried out to eliminate the grid side step-up-transformer from the SliM-based WTPGS [88]. Pair of generator coils of SliM were used to generate multiple sources for the MMC converter as shown in Fig. 14. A similar converter concept was also proposed in [89]. In 2008, an 11 kV, 25-level converter with 2.5 kW modular PMG (72 isolated stator coils) was designed [90]. A multi-coil generator-based wind turbine system is shown in Fig. 15. This multi-winding generator requires a special winding arrangement (which increases the weight and volume) and complicated control strategies. An improved control strategy was proposed and verified on a similar generator converter system [91,92]. The rotor diameter of a low-speed, direct-drive synchronous generator is several times larger than that of a conventional gearbox based high speed generator. Although recently a few manufacturers such as Enercon and Siemens have shown that advanced direct drive turbines have a weight comparable to gearbox based turbines, the direct drive turbines are generally considered to be expensive, heavy and large. The most critical drawback of the multi-coil generator and MMC converter-based wind power generation system is the lack of electrical isolation between the grid and turbine generator.

8.1.2. Multiple generators-based medium-voltage converter

A transformer-less wind power generation structure with several parallel six-phase PMSGs has been proposed in [93], where a few of six-phase generators are placed in the turbine nacelle. A multiple generators-based wind turbine system is shown in Fig. 16. All the generators are driven by the same wind turbine and each stator winding generates an isolated source for an H-bridge inverter cell of the MMC converter. The MMC converter generates medium voltage AC output, which can be connected to the medium-voltage network directly. The proposed structure requires multiple generators, depending on the number of levels of MMC converter. The multiple generators increase the system volume and weight and make the system impractical especially in medium-voltage applications, where a high number of levels is required. Moreover, the grid isolation is the critical issue in the proposed converter system.

8.1.3. Medium-frequency magnetic link-based medium-voltage converter

Compared with the conventional transformers operated at the power frequency, the medium-frequency (in the range of a few kHz to MHz) transformers have much smaller and lighter magnetic cores and windings, and thus much lower costs. A medium-frequency magnetic-link-based novel medium-voltage MMC converter system was proposed as shown in Fig. 17, to eliminate the grid-side step-up-transformer, which is desirable for both onshore and offshore WTPGS [94–96]. In 2013, an amorphous alloy-based medium-frequency magnetic-link was proposed to generate isolated and balanced multiple dc supplies for the MMC converter [97,98]. In order to design optimal medium-frequency magnetic-link, the performances of different amorphous alloys were analyzed in [99]. This medium-frequency magnetic-link-based medium-voltage converter eliminates the grid side step-up-transformer without changing the design of traditional generators. A three-phase medium-voltage converter-based wind power generation system is shown in Fig. 18. The medium-frequency magnetic-link medium-voltage converter-based wind turbine system has the following new features compared with the existing similar systems: (1) no requirement for special or multiple generators; (2) an inherent dc-link voltage balance due to common magnetic-link; (3) direct gird connection without using step-up-transformer and line filter; (4) an overall compact and lightweight system; and (5) an inherent minimization of the grid isolation problem through the medium-frequency magnetic-link.

8.1.4. Matrix converter-based medium-voltage converter

The matrix converter (MC) is a unique topology AC to AC power converter that eliminates the need for an intermediate DC conversion and the passive reactive filter components associated with

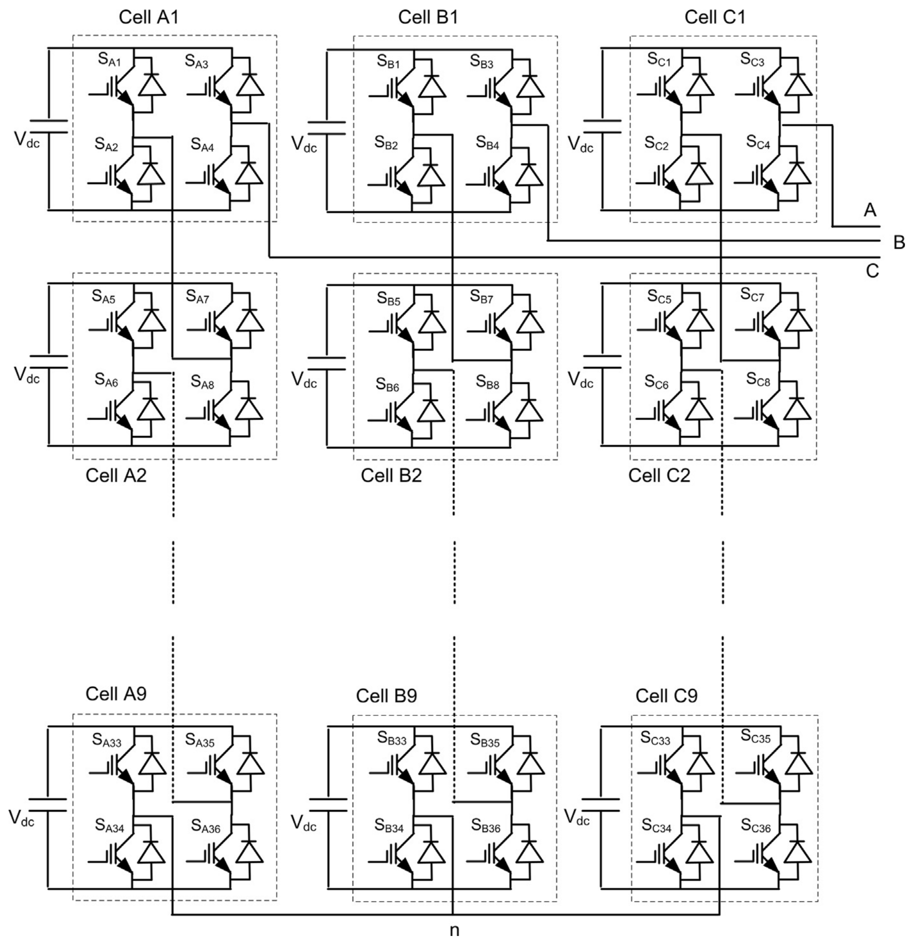


Fig. 13. Three-phase 19-level MMC converter.

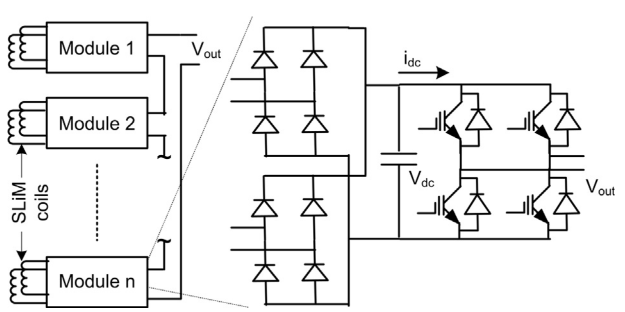


Fig. 14. SliM-based medium-voltage converter topology.

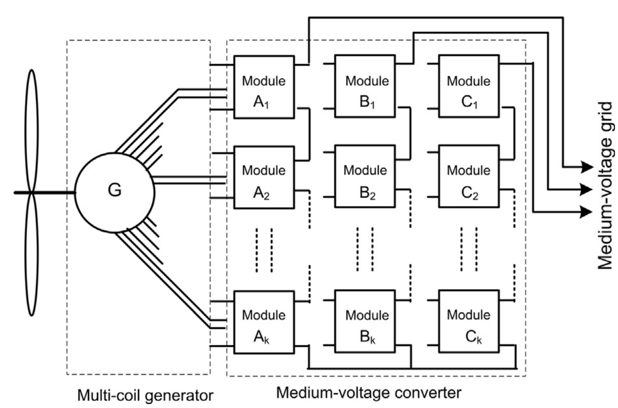


Fig. 15. Multi-coil generator-based WTPGS.

this DC-link [100,101]. The converter consists of an array of bidirectional switches positioned at the intersection points of the input and output phases. The output is synthesized by the selective closings and opening of the switches. A combination of MC topology and multilevel converter topology was investigated in [102].

MCs offer the potential for significant size and weight reductions in power converter applications due to the absence of any large energy storage elements, such as DC-link capacitors [103]. Due to this special feature, the MC has attracted considerable attention in recent years [104,105]. A disadvantage of the MC is the intrinsic limitation of the output voltage; without entering the over-modulation range, the maximum output voltage of the MC is 0.866 times of the input voltage.

A high power MC converter was patented in 1999 [106]. In 2005, an 150 kV A MC was fabricated and tested for electric vehicle applications [107]. In 2007, the first multi-winding phase-shifted transformer-based medium-voltage multi-modular MC topology was proposed in [108]. The MC topology was implemented commercially in 2008 [109]. In 2011, single-phase output matrix converter (SPMC)-based medium-voltage motor drive system was implemented in [110,111] and its application in wind power system was proposed in [112]. The converter topology is shown in Fig. 19. Split winding PMSG wind turbine generators based modular MC was also investigated in [113] to eliminate the grid side transformer from the wind turbine power generation

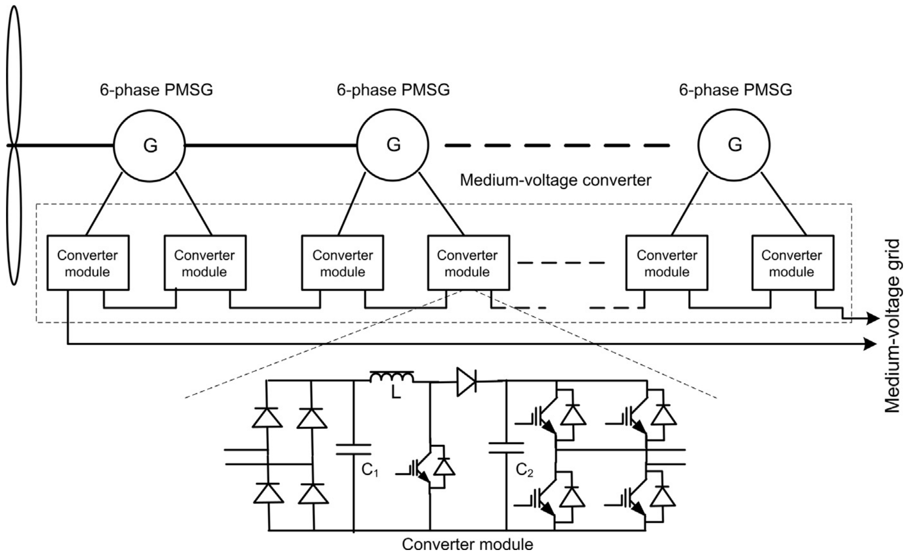


Fig. 16. Multiple generators-based wind turbine system: single-phase layout.

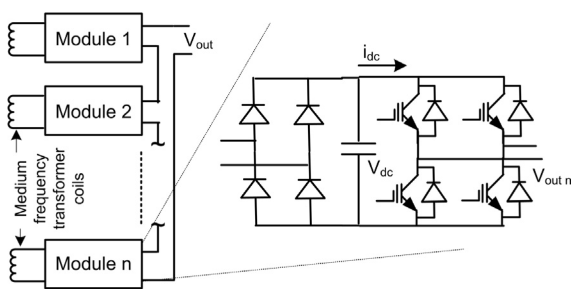


Fig. 17. Medium-frequency magnetic-link-based medium-voltage converter topology: single phase layout.

systems. Although this design does not require special machine, it needs several generators.

8.1.5. Medium-voltage DC converter

Recently, a transformer-less generator-converter concept has been introduced for lightweight HVDC WTPGS [114,115]. The iron-less stator generator with several stator segments and modular AC/DC converters was used in the proposed system as portrayed in Fig. 20. In 2012, a minimum weight dual active bridge converter was proposed to reduce the weight of WTPGS [116].

8.2. Medium-frequency transformer-based system

Increasing the operation frequency can greatly reduce the physical volume of the transformer, which has been widely used in switched mode power supplies. Operated at 1.2 kHz, the weight and size of a 3 MW transformer can be less than 8% of an equivalent 50 Hz unit [117]. For high-power applications, a new type of transformer employing new magnetic materials with higher saturation flux density levels and lower core losses, and efficient semiconductor devices with fast switching possibilities, high blocking capabilities, and higher power densities, known as the power electronic transformer, was investigated in [118]. In 2004, an HVDC wind power generation system was introduced [119]. The proposed converter system consists of voltage source converter and cycloconverters connected through medium-frequency transformers. A new HVDC wind farm with medium-frequency transformer was introduced in [117,120] as shown in Fig. 21.

Design considerations of a 3 MW medium-frequency transformer for offshore wind farms were proposed in [121]. A multi-generation turbine and MC-based HVDC system has been proposed in [122]. That proposed system consists of MCs, high-frequency transformers (HFT) and full bridge rectifiers as shown in Fig. 22.

8.3. Superconducting generator-based system

Superconductors are materials which carry almost loss-free electrical currents, when cooled down below their critical temperatures. Low temperature superconductors have found their market in magnetic resonance imaging (MRI) diagnostics systems and in high energy physics laboratories. From 1975 to 1979, a detailed conceptual design study of 300 and 1200 MVA steam turbine generators utilizing superconducting field windings was carried out in [123,124]. The high temperature superconductor (HTS) materials were discovered in 1986 by International Business Machines (IBM) researchers and then gradually improved with a concomitant reduction in cost.

The current densities of the superconductors are over 100 times higher than those in conventional copper conductors. Therefore, a superconductor based compact and lightweight generator may reduce the weight of wind turbine power generation systems. The optimum weight for a 10 MW direct drive PMG is about 300 t, whereas the projected weight of a 10 MW HTS generator is approximately 150–180 t [125,126]. There are several successful tests of the first generation models and the prototypes of motors and generators using HTS [127–130]. In 2005, Siemens developed rotors using superconducting field windings. American Superconductor Corporation (AMSC), in collaboration with Northrop-Grumman, built the world's highest torque HTS motor for the US Navy at 36.5 MW using bismuth based superconductor (BSCCO) wire. This was delivered in 2007. The electromagnetic characteristics of a 10 MW superconducting wind turbine generator were studied in [131]. Recently, Sway Turbine and Windtec Solutions have been developing a 10 MW wind turbine generator, which is called the SeaTitan and this is considered to be the world's most powerful turbine [44,45]. The SeaTitan wind turbine design employs an HTS generator, which is significantly smaller and lighter and expected to be commercially available by 2015 [132]. There are several challenges, like the price of superconducting

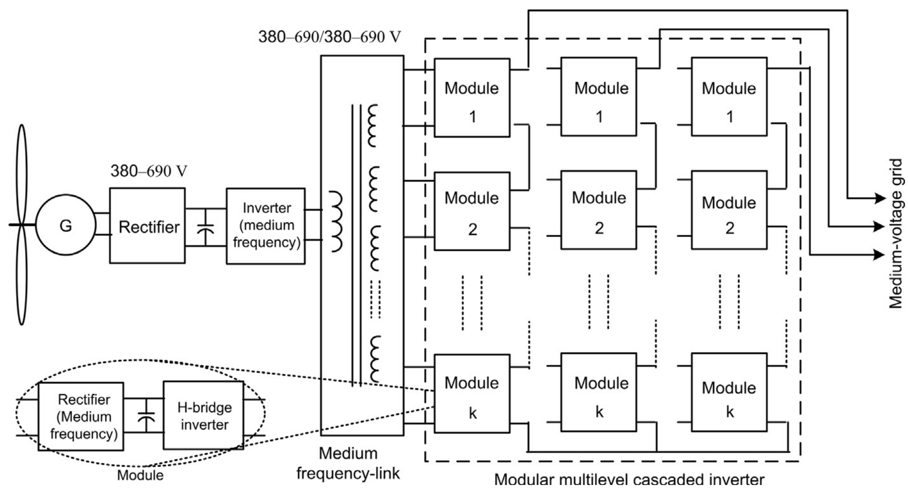


Fig. 18. Detailed layout of medium-frequency magnetic-link medium-voltage converter-based WTPGS.

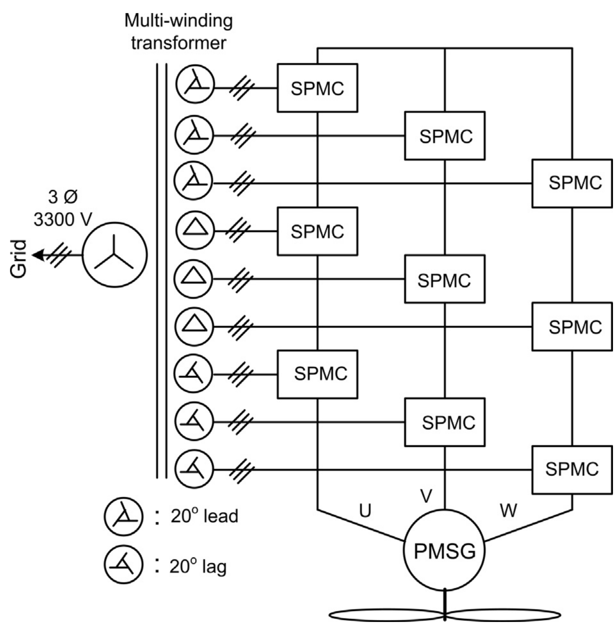


Fig. 19. SPMC medium-voltage converter-based WTPGS.

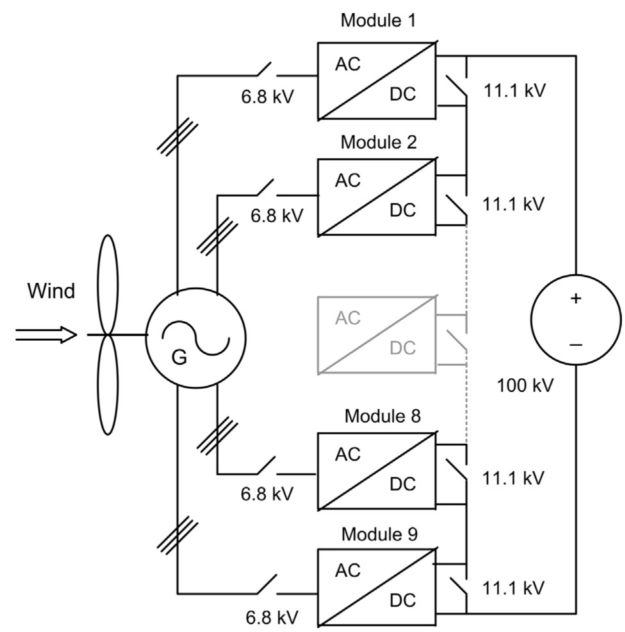


Fig. 20. Wind turbine with segmented stator generator and modular converter.

wires and cooling technology, which must be addressed before large scale utilization can be obtained.

9. Discussion

With the fast development of semiconductor technology, there goes on a continuing race to develop semiconductor power switching devices, e.g. the insulated gate bipolar transistors (IGBTs), of higher and higher voltage and current ratings for utilization in high-power systems. Many recent generations of devices, such as 2.5, 3.3, 4.5 and 6.5 kV IGBTs, are suitable for 2.5 kV or lower voltage inverter systems with traditional 2-level topology. Although 3.3, 4.5 and 6.5 kV IGBTs are available on the market, they are still costly. The low-voltage devices, such as 0.6, 0.9, 1.2, 1.7 and 2.5 kV IGBTs are not only matured in technology but also inexpensive. Therefore, the series–parallel connection of low-voltage rated semiconductors can be a cost-effective solution for medium-voltage inverter applications. Multilevel converters, especially the MMC topology, may be a natural choice to design medium-voltage converters using low-voltage rated devices. Recently, the MMC multilevel converter has attracted significant attentions to eliminate the step-up-transformer from the wind turbine nacelle. However, the MMC converter requires multiple isolated and balanced DC supplies. In this instance, a multi-coil special generator [90–92], multiple traditional generators [93] and medium-frequency common magnetic-link [94–96] have been proposed in recent years.

The first two solutions require a special generator or multiple traditional generators, which may increase the system weight, volume, complexity and cost. The recent advances in magnetic materials have led to the development of a compact and light weight, medium-frequency magnetic-link, which would be a possible solution to generate multiple isolated and balanced DC supplies from a single wind turbine generator. In this context, the third solution eliminates most of the critical limitations of the first two solutions. Up to now, many kinds of soft magnetic alloys with high magnetic flux density combined with low core loss have been developed. The amorphous alloy and nanocrystalline materials have excellent magnetic characteristics for medium-frequency

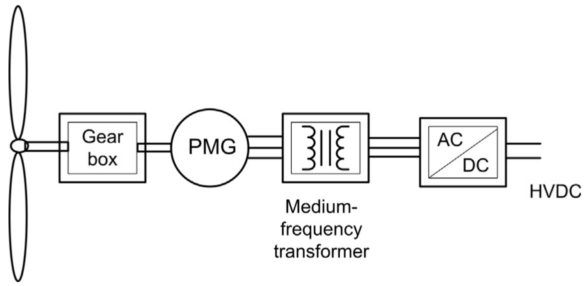


Fig. 21. Wind turbine with permanent magnet generator and MFT.

applications, such as high permeability, high saturation flux density and relatively low core losses. With these advanced magnetic materials the medium-frequency magnetic-links have much smaller and lighter magnetic cores and windings, and much lower costs. Therefore, the medium-frequency magnetic-link based medium-voltage converter can be an excellent choice to eliminate the step-up transformer from the wind turbine nacelle.

The MC provides direct AC to AC conversion, which eliminates the need for an intermediate DC conversion. However, the complexity of phase shifted multi-winding transformer or split winding PMSG may limit the voltage level of the converter. The modular converter based medium-voltage DC converter is suitable for HVDC transmission system. This converter may interconnect the wind turbine generator to the HVDC transmission line directly. The segmented stator would increase the volume, weight and complexity of the wind turbine generator, and needs special design.

Since increasing the operation frequency can greatly reduce the physical volume of a transformer, replacing the power-frequency step-up-transformer with a medium-frequency transformer can be a possible option to reduce the weight and volume of the wind turbine nacelle. However, the implementation of medium-frequency medium-voltage transformer is critical, especially the insulation issue.

The mass of a turbine generator is much higher than that of a turbine step-up-transformer. The generator weight reduction is the prime option to reduce the weight of wind turbine nacelle. In this instance, superconductor based generators have attracted considerable attentions and become top research tropic in recent years. The estimated weight of a 5 MW superconducting generator is only 34 t. Therefore, large weight can be reduced by replacing copper conductor generator with a superconducting generator. The recent advances in superconductor materials have led to the development of compact and light weight wind turbine generators. Still there are several challenges, like price of superconducting wires and cooling technologies which must be addressed before large scale utilization can be obtained.

10. Conclusion

The power rating of modern offshore wind turbines has increased up to 10 MW in order to harvest more energy and thus reduce the cost per megawatt of capacity. The construction and installation costs of these multi-megawatts turbines are really high and critical in offshore areas. The weight and volume reduction of the power generation system might be a solution to this issue.

In this context, the grid side step-up transformer-less system has drawn a high degree of attentions. The medium-voltage converter may feed the wind power to the medium-voltage grid directly without using the step-up-transformer and line filter. The medium-frequency magnetic-link-based MMC converter may be an excellent choice to develop medium-voltage converters. New development of the HTS generator is another attractive solution to reduce the weight of WTPGS. By combining these two most attractive concepts, it may be possible to design a future wind turbine, which can reduce the system weight and size as well as save a large amount of turbine construction and installation costs. Although the current research and development has brought these technologies to a certain level, more research still needs to be done for further development of power converters and turbine generators as new magnetic materials and new high-power semiconductor devices enter the market.

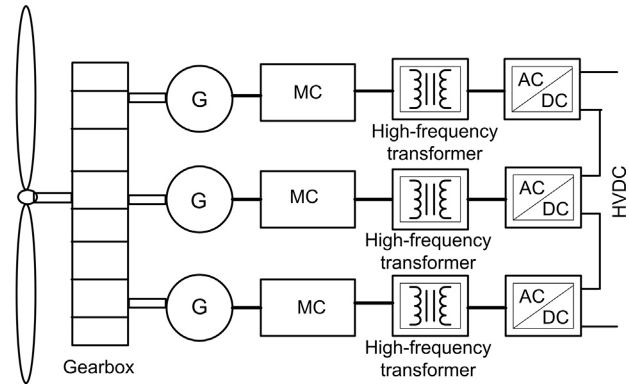


Fig. 22. Wind turbine with MC and multi-generation system.

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